Throughput Fairness Analysis of Reservation Protocols of WiMedia MAC

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Abstract— WiMedia standardized a fully distributed high data rate communication using ultra wideband (UWB) for wireless personal area networks (WPANs). WiMedia MAC provides asynchronous data communication service by Prioritized Channel Access (PCA) and isochronous service by Distributed Reservation Protocol (DRP). In this paper we propose three different approaches to analyze the reservation protocols, PCA and DRP, of WiMedia’s Medium Access Control (MAC). In the first two approaches we keep the portions of the superframe fixed for DRP and PCA traffics while the third approach follows random reservation. To test out the throughput fairness of PCA and DRP traffic by proposed approaches we present a scenario of connected nodes and incoming nodes with mixed traffic (video, VoIP and best effort). By means of simulations using Omnet++, we show that the system offers higher throughput by using approach 3, which provides access to medium by Hard, Soft and PCA reservation. The throughput fairness is also estimated for the three approaches by using Gini index.

Keywords: Distributed Reservation Protocol (DRP), Ultra-Wideband (UWB), Wireless Personal Area Network (WPAN).

I. INTRODUCTION

Medium access control (MAC) layer protocols plays an imperative role to handle the challenging QoS provisioning issues by efficiently controlling the accessing and utilizing of wireless channels. In July 2008, WiMedia Alliance and European Computer Manufacturers Association (ECMA) International announced a joint development relationship. Both Partners agreed upon the development of specific standards, which will be conducted jointly and by mutual cooperation of the engineers of member companies. For high data rates wireless personal area networks (WPANs) the ECMA standard [1] defined Physical and MAC layers which offer a number of policies and control mechanisms to ensure the quality of service (QoS) provisioning. Ultra Wideband (UWB) offers a number of advantages over other short range technologies e.g. high data rates, low power and precise positioning, which makes it more suitable for the WPAN. UWB supports various data rates ranging from 110 to 480 Mbps over distances up to 10 meters [2].

In general MAC protocols can be contention free and contention based, and some proposed ones are a combination of both. Contention free protocols require more challenging mechanisms to handle access to the channel by competing nodes with different traffic types. For this reason WPANs are designed as centralized or decentralized. IEEE 802.15.3 [3] is an example of centralized approach where the devices form a cluster called Piconet, and a coordinating device, called Piconet Coordinator (PNC), manages all the members of the piconet. The PNC has the knowledge of the member nodes and assigns the available Medium Access Slots (MASs) often on Time Division Multiple Access (TDMA) approach. But the centralized approach has a number of limitations e.g. QoS provisioning, scalability of the network and if the PNC fails the whole network goes down. Furthermore, the connectivity of multiple Piconets is costly in terms of inter-piconet interference and leads to degraded performance [4]. To address these problems a distributed MAC, which is based on multiband orthogonal frequency-division multiplexing (MB-OFDM), has been proposed by WiMedia Alliance [5] and ECMA [1]. Both IEEE 802.15.3 and WiMedia MAC are based on slotted superframe. Each node reserves slots in the superframe, by using a reservation protocols defined in the WiMedia standard. In this paper we propose three approaches to analyze the reservation process of WiMedia MAC.

The rest of this paper is organized as follows: In section II we present an overview of the WiMedia superframe and DRP, followed by related work in section III. In section IV, we present the proposed approaches for analysis. Section V represents the proposed scenario and simulation setup followed by results and discussion. Finally, we conclude the paper in section VI.

II. PRELIMINARIES

This section presents an overview of the UWB superframe structure, DRP and Gini index.

A. Superframe structure

The UWB MAC channel time is divided into superframes. The total duration of the superframe is 65,000 μs and is composed of 256 MASs with duration of 256 μs each [1]. The superframe is further divided into two main parts, a Beacon Period (BP) and Data Transfer Period (DTP) as shown in figure 1. In BP each user transmits its own beacon frames, which contain Information Elements (IEs). The users put their timing and control information in these IEs to access the channel in a fully distributed manner and synchronization. Incoming novel users use the information contained into the beacon frames to identify empty beacon slots, occupy it and transmit their own beacons. The beacon frames are also used to reserve MASs in the DTP.
The MASs are reserved, modified or released via DRP or accessed via Prioritized Contention Access (PCA). DRP is used to reserve the MASs mostly for isochronous traffic, for nodes that need guaranteed access to the medium, while PCA provides differentiated channel access to the medium similar to IEEE 802.11e. When a node wants to reserve MASs, for data transmission or reception, it negotiates with its neighbors via DRP IE and reserve a set of MASs. The DRP frame contains a number of IEs representing different pieces of information. The DRP contains the control IEs which show owner, status of reservation, reason codes, reservation types and some more information about the reservation requests, to solve conflicts between users [1]. The device that wants to start the reservation process is called the owner and the device that receives the information for reservation is referred as target. The type of reservation can be Hard, Soft, PCA, Private or Alien BP. The Reservation status indicates the status of the DRP negotiation process, which shows whether a reservation is under negotiation, in conflict or established. The Reason Code is used by a reservation target which shows whether a DRP reservation request was successful or not.

A DRP IE contains one or more DRP Allocation fields, which are encoded using a zone structure. The zone structure is split into 16 zones numbered from 0 to 15 starting from the BP. The zones are further divided into isozones which are separated by fixed intervals. In this two-dimensional structure of the WiMedia superframe each column of the superframe matrix is called an allocation zone, as shown in figure 2. In the reservation allocation IE each node includes a Zone bitmap and a MAS bitmap, where Zone bitmap identifies the zones that contain reserved MASs and the MAS bitmap specifies which MASs in the zones identified by the Zone Bitmap field are part of the reservation. The reservation of MASs in the zones follows certain rules to ensure fairness. Details about this process are available in [1].

C. Reservation Fairness using Gini Index

The Gini index represents a measure of statistical dispersion developed by the Italian statistician and sociologist Corrado Gini [14]. The Gini coefficient is a measure of the inequality of a distribution, 0 expressing perfect equality and a value of 1 expresses maximal inequality. We used Gini index to calculate the throughput fairness by the following formula. Let \( l \) and \( k \) be two users having observed throughput represented as \( \Theta \), and the number of average throughput observed in the system represented as \( n \); then the Gini index for throughput fairness is therefore calculated as shown in the equation 1.

\[
G = \frac{1}{2n} \sum_{k=1}^{n} \sum_{l=1}^{n} \left| \frac{\Theta_{av_k}}{\Theta_{av_l}} - 1 \right|
\]

where

- \( \Theta_{av_k} \) is the observed Average Throughput value of users \( k \) and \( l \).
- \( n \) is the number of Average Throughput observed.
- \( \Theta_{av,R} \) is the Average Throughput of all users placed within the coverage 'R'.

III. RELATED WORK

DRP, characterized by different parameters and approaches, has been analyzed in previous works both by analytical models and simulation. MAC layer has been modeled as a queuing system by Markovian arrival process (MAP) and phase type distribution (PH), and the throughput was analyzed with respect to traffic load in [6]. In [7] the authors presented a study on the delay performance of DRP channel access for Multi-band OFDM Alliance (MBOA) UWB MAC by a bi-dimensional Markov chain model, where one dimension represents queue size distribution and the other is for allocated slots. UWB based WPAN, where physical layer adaptive modulation and coding is coupled with the DRP and the delayed acknowledgement schemes at the link layer, has been studied in [8]. An analysis based on traffic type and priority reservations was presented in [9], while [10] considers the blocking probabilities of the reservation process.

Another analytical model for DRP, based on shadowing effect which varies the channel condition, has been studied in [11]. The authors consider both hard and soft DRP, and have proposed a channel model to describe the dynamic behavior of the UWB shadowing channel at the packet level. On a first-come first-served basis a contention-free distributed protocol has been analyzed for delay and throughput fairness in [12]. A study on the delay performance of DRP under different reservation patterns under the dynamics of UWB shadowing channel has been presented in [13]. The authors have modeled the system as a discrete-time single server queue with vacation time represented by the quasi-birth and death process to analyze the performance of DRP. In this paper we show how the incoming nodes with mixed traffic types affect the reservation process of a already connected network. We have used hard, soft and PCA reservation types to allocate the MASs to nodes with mixed traffic. The incoming nodes to the system use first come first served scheduling to access the channel.

![Figure 2. Superframe's two dimensional view.](image-url)
IV. PROPOSED APPROACHES

In this section, we present our approaches to analyze the WiMedia’s MAC reservation protocol.

The DRP plays an important role to guarantee the QoS of isochronous traffic. The devices use beacon IEs to reserve the MASs in the superframe to transmit data. Since the MASs are allocated by DRP without prior knowledge of the traffic to ensure overall traffic load balance or fair distribution of the MASs among the nodes, we propose approaches to test the performance of the reservation based on the traffic types of incoming mobile nodes in the system. The nodes can use the DRP in a selfish manner to occupy the MASs for extended duration, ignoring the waiting nodes or less prioritized nodes with best effort traffic. This selfish approach not only restricts the size of the network but also degrades the performance. Furthermore, the standard [1] defines a number of DRP reservation methods, e.g., Hard, Soft, Private, PCA, etc. So the MAS allocation needs to be carefully handled during the beacon period and proper MAS access mechanisms should be used.

In our approaches, we have divided the superframe into parts, for DRP and PCA users to check the effect on throughput and to keep a balance between the two reservation mechanisms with different types of traffic.

A. Approach 1

The reservation process becomes more challenging when the nodes are mobile, and detached nodes or new incoming ones want to join the network. In the first approach, we divided the superframe into two equal parts, DRP part and PCA part as shown in figure 3. The stations reserve the MASs based on hard DRP, meaning that once they occupy specific MASs, they hold them for their whole data transfer, and they have to release them when their data finish. The isochronous traffic nodes cannot reserve the PCA MASs and PAC nodes cannot occupy the DRP MASs. The incoming nodes are not allowed to use the relinquish request IE once a MAS is reserved as Hard. The purpose of this approach is to check whether we can provide a balance to the MAS allocation by DRP and PCA, and also to check the effect on PCA traffic in the presence of hard reservation for both types of traffic.

B. Approach 2

In the second approach, we reserve more MASs for the isochronous traffic. The nodes can reserve MASs by both Hard and Soft reservation. The isochronous traffic nodes cannot reserve the PCA MASs and the same rule is applied to the PCA reservation. The incoming nodes to the system can use the relinquish request IE to inform the neighbors to release the MASs occupied by Soft reservation. The PAC based reservation nodes will back off once they find the PCA portion of MASs saturated.

C. Approach 3

In this approach, we use a dynamic reservation based on the traffic type and do not specify or fix the MASs for DRP and PCA reservations, as shown in figure 5. Nodes can reserve MASs by both Hard and Soft reservation and PCA. The isochronous traffic nodes can reserve the PCA MASs if they are available. If a node with isochronous traffic wants to enter the system, it will first look for free MASs, then will back off and wait for a short time for PCA MASs, and finally it will request for releasing the MASs reserved by Soft reservations. Nodes that are connected and those which are entering into the system use the DRP service primitive parameters, e.g., desired bandwidth, available bandwidth and minimum bandwidth. The nodes use these parameters and estimate how much bandwidth they need and how much is available in the system.

V. SCENARIO AND SIMULATION SET UP

In this section, we present our scenario for simulation, in which we have a connected network of 6 nodes and incoming mobile nodes, as shown in figure 6. For testing purposes, we consider random arrival of nodes with mixed traffic. The above scenario was simulated using Omnet ++ 4.1 [15], an open source simulator, and results are generated for the analysis of DRP and PCA under the rules of proposed approaches. The connected network is composed of 6 nodes and the number of incoming nodes is different among the simulations. The nodes joining the network have a mobility of 0.5m/s, and we are using constant speed mobility model. All the nodes have a maximum transmission power of 1 mW. The data rate is 480 Mbps and the traffic type is mixed. The scheduling of the allocation process is maintained on first-come first-served bases. The duration of the time slots is 256 μs.
VI. SIMULATION RESULTS

Initially when the system is not saturated, the system can accommodate incoming nodes with both types of reservation and using any of the three approaches. On the other hand, with the arrival of new nodes the probability of getting the MASs to transmit data gets lower, especially for isochronous traffic. Figure 7 shows the amount of allocated MASs to DRP and PCA reservations for the proposed approaches. In case of approach 1 the allocated MASs to DRP nodes are less because of the Hard reservation, whereas MAS allocation is high to PCA traffic nodes because of large portion of superframe is utilized by best effort traffic nodes. Approach 2 provides more flexibility to the isochronous traffic nodes by using both hard and soft reservation but still cannot reserve the free MASs maintained for incoming PCA nodes. The incoming nodes scan the reserved MASs and adopt the policy to reserve the MASs in a more flexible way in approach 3, which thus provides a more balance representation of MASs allocation to both isochronous and asynchronous traffic nodes.

Figure 7 shows the throughput of the system with the arrival of nodes using DRP and PCA reservation. Initially the number of nodes in the system is less and there are free MASs available for incoming reservations. The proposed approaches contribute with different results to the system overall throughput because of the different reservation types and rules. Approach 3 shows high throughput because of soft reservation and PCA’s MASs occupation. The throughput of the system reaches its maximum for 20 nodes, thereafter it remains constant because of saturation. The throughput of approaches 1 and 2 is lower because of the fixed MASs and it depends on the traffic of nodes joining the system. Therefore the throughput of the system depends on the incoming nodes’ traffic type, rate, and also the adopted approach.

The number of packets in the system and their success and drop ratios, depend on the flexibility of the approach, rate of arrival, rules and policies applied to incoming traffic classes and buffer size of the nodes. In case of Hard reservation, keeping the superframe reservation portions fix led to high ratio of dropped packets. On the other hand, providing more flexibility to the reservation by utilizing the available MASs and by keeping a balance between PCA and DRP Hard and Soft reservation, the number of packet drops decreases. The packet drops of the incoming nodes for the three approaches are shown in the figure 9.
The Gini index is calculated according to equation 1, by considering 30 nodes. As shown in Figure 10, Approach 3 gives us better fairness in term of throughput for all the nodes, as MASs can be relinquished by utilizing Soft reservation and also by estimating the number of available MASs for a specific incoming node.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed three different approaches to analyze the reservation protocol of WiMedia MAC for throughput fairness, for both isochronous and asynchronous data traffic types. In approach 1 we kept half the superframe Hard-reserved for DRP, and half for PCA traffics. In approach 2 we provided flexibility to DRP based reservation by applying Soft reservation, and also by leaving more MASs for nodes entering into the system. Based on the limitations of these two approaches, we proposed Approach 3, which reserves the MASs using Hard, Soft and PAC reservation types, supported by standard’s bandwidth estimation primitives. The simulation results show that Approach 3 provides more fairness to the system, compared to the other approaches. An analytical model for the throughput fairness of these approaches is the future direction of this work. Additionally, queue modeling and trade-off between different system parameters shall be considered.

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